3.0 DAM OPERATION

The dam owner must possess specific knowledge about the dam and its appurtenant works to operate and maintain the dam in a safe and responsible manner. The owner must also have an understanding of the watershed area that contributes water to the reservoir, as well as impacts the reservoir may have on downstream areas. This chapter provides guidance to help the dam owner operate his/her dam more efficiently.

3.1 THE WATERSHED AND RESERVOIR LEVELS

3.1.1 The Watershed

The watershed is the upstream area of land that drains into the reservoir. The dam owner should have an understanding of the size and characteristics of the watershed, and the hydrologic cycle of water. The earth's hydrologic cycle is never-ending and is continuously at work in every watershed. During the cycle, a drop of water may be in various states and locations. Initially, water evaporates from the land surface and oceans as water vapor to become part of the atmosphere. The water vapor is transported and lifted into the atmosphere until it condenses and precipitates on the land and oceans. Precipitated water may be intercepted by vegetation, become overland flow on the ground surface, infiltrate into the ground, flow through the soil as subsurface flow, and discharge into streams and lakes as surface runoff. Large amounts of the intercepted water and surface runoff returns to the atmosphere through evaporation. Infiltrated water may percolate deeper to recharge the groundwater, and later emerge from springs or as seepage into streams, to form surface runoff. Finally, this water may flow out to the ocean or evaporate into the atmosphere. Water that infiltrates in the ground may eventually drain out of the ground into streams, rivers, and lakes within the watershed, or it may infiltrate deep into the ground and travel out of the watershed area. The precipitation that is intercepted by the vegetation, and groundwater that is taken up by the vegetation, may transpire into the atmosphere as water vapor. Thus, the hydrologic cycle is a continuous process of evaporation and precipitation.

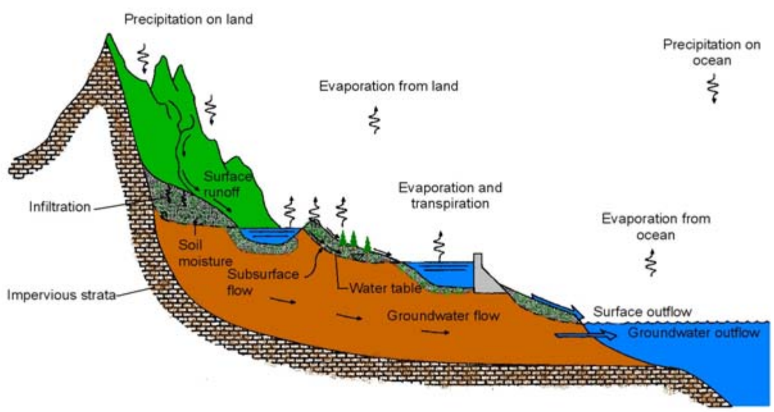

Figure 3-1 Typical watershed hydrologic cycle.

During a rain storm, it is too humid for the precipitation to evaporate or transpire by any appreciable amount; therefore, most precipitation either soaks into the ground or runs off into streams, rivers, and lakes. When it is not raining, the water that flows into the reservoir from the streams and springs is usually called the base flow, or normal flow. The base flow comes from the precipitation that infiltrated into the ground during the storm events. The base flow is typically very small compared to the flows from runoff during storm events.

The amount and rate of water that flows into a reservoir is dependent on many factors in the watershed, including the amount of precipitation, the rate at which the precipitation falls, the soil types, the land use, the topography, the size of the watershed, and distance across the watershed. Rapid flows into a reservoir can result in a dramatic rise of the water levels. High inflows are usually the result of heavy precipitation within a watershed. However, other combinations of climatic and ground conditions can cause large amounts of runoff. For example, a moderate rain on frozen ground, combined with snowmelt can produce a large amount of runoff. This is due to the fact that there would be little or no infiltration when the ground is frozen, and nearly all the rainfall would move as surface runoff.

One of the best ways for a dam owner to better understand his watershed is by compiling a history of precipitation, ground conditions, and corresponding spillway flows. Over time, the owner will become aware of the length of time between rainfall and flow increases at the dam.

3.1.2 Reservoir Levels

The normal pool level in the reservoir is the elevation of the water surface when it is not raining, and after flood flows from a storm have subsided to the base flow. For most reservoirs, it is the elevation of the principal spillway crest. The dam's storage capacity, freeboard, and spillway discharge capacity are usually based on the normal pool level. Therefore, it is important for every dam owner to know the normal pool level. The M&M Plan should include the normal pool elevation on the Dam Background Data Sheet.

The M&M Plan should also specify how and when to release water during normal and flood times, what equipment is needed, and who is responsible. It should take into account any minimum releases that may be required for downstream users, or for fishery and wildlife-habitat protection. These minimum flows should be determined in cooperation with downstream water users, and in some cases, the Indiana Department of Natural Resources.

The owner should consider the riparian rights of downstream property owners when releasing or impounding water.

Reservoir levels needed to protect upstream users should also be specified in the M&M Plan, if required. This may require that minimum, normal, and maximum water levels be established. If the reservoir level is raised, flowage rights or easements must be checked. The design storm event for maximum water level determination may be stipulated by a local or state agency, so the dam owner must be familiar with all applicable regulations. For a properly designed dam and reservoir area, all significant structures should be placed above maximum water levels.

Figure 3-2 A slope stability issue required drawdown of this reservoir until improvements were made (siphons used).

Reservoir pool levels are often controlled by spillway gates, lake drain and release structures, and flashboards. A general rule of thumb for safety is that pool level drawdown rates should not exceed 1 foot per day, except during emergency situations. Relatively flat slopes or slopes with free draining upstream zones can withstand more rapid drawdown rates, up to a maximum of 6 inches per day. Rapid drawdown of the pool may leave the upstream slope saturated and without support, and could result in sloughs and slides. If there is any question about the allowable drawdown rate, a qualified dam safety professional should be contacted. Listed below are conditions or instances that could require the pool level to be permanently or temporarily adjusted:

- A problem develops that requires the permanent pool to be lowered. Drawdown is temporary until the problem is solved.
- Water is released at a controlled rate to the downstream channel to supplement streamflow during dry conditions. This action may temporarily lower the reservoir level.
- Water-supply reservoir levels will fluctuate according to the service area's demand for water and inflow rates. Flashboards are sometimes used to permanently or temporarily raise the pool level of water-supply reservoirs. Flashboards should not be installed or allowed unless there is sufficient freeboard remaining to safely pass the design flood.
- The reservoir level is drawn down to facilitate repair of boat docks, to retard growth of aquatic vegetation along the shoreline, or to provide additional storage for spring runoff.
- Pool levels are sometimes adjusted for recreation, hydropower, or waterfowl and fish management.

3.2 OUTLETS AND DRAINS

The reservoir drain, or outlet, should always be operable so that the pool level can be drawn down in case of an emergency or for necessary repairs to the dam. Drain valves or gates that have not been operated for a long time may get stuck from corrosion, or blocked with sediment or other debris. On the other hand, if the valve cannot be closed after it is opened, the impoundment could be completely drained. An uncontrolled and rapid drawdown could also induce more serious problems such as downstream flooding and erosion, or slides in the saturated upstream slope of the embankment. Therefore, before operating a valve or gate, it should be inspected and all appropriate parts lubricated and repaired. It may also be prudent to advise downstream residents of large or prolonged discharges.

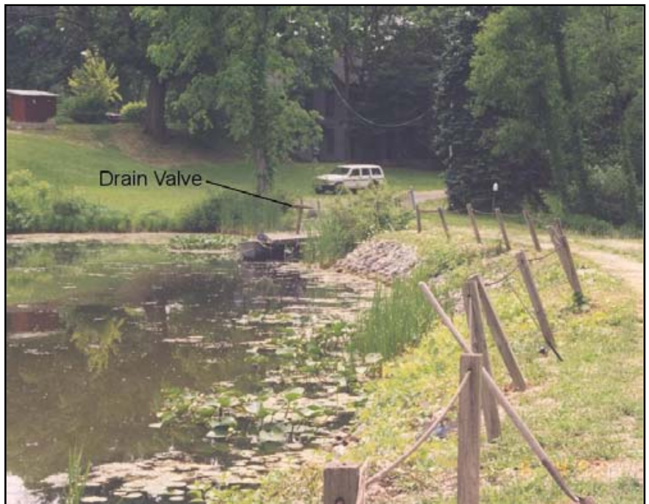

Figure 3-3a Outlet valve located under pier (not recommended) built over the riser. Figure 3.3b shows close-up of valve stem.

To test a valve or gate without lowering the lake, the drain inlet upstream from the valve must be physically blocked. Some drain structures have been designed with this capability and have dual valves or gates, or slots for stoplogs (sometimes called bulkheads) located upstream of the drain valve. Divers can be hired to inspect the drain inlet and may be able to construct a temporary block at the inlet for testing purposes.


Figure 3-3b Make-shift valve stem handle.

Other problems may be encountered when operating the reservoir drain. Sediment can build up and block the drain inlet. Debris can be carried into the valve chamber, thereby hindering its function if an effective trash rack is not present. The potential that these problems will occur is greatly reduced if the valve or gate is operated and maintained periodically. The gate or valve controlling the drain should be operated from the fully closed to fully open position at least twice a year. It is preferable that the drain be operated four times a year. Early detection of equipment problems or breakdowns and confidence in equipment operability are benefits of routine inspection and operation. Figure 3-3a shows a make-shift pier constructed over the principal spillway riser pipe with the valve actuator projecting above the pier. Figure 3-3b shows a close-up view of the valve actuator; a hole was left in the pier for inflows to the riser (this practice is not recommended).

The best location for drain valves is upstream from the centerline of the dam. Older dams often have drains with valves at the downstream end. This design results in the entire conduit being under the constant pressure of the reservoir when the valve is closed. If a leak should develop in that portion of the conduit within the embankment, saturation, erosion, and possibly failure of the embankment could occur in a short period of time. A depression in the soil surface over the pipe may be a sign that soil is being removed from around the pipe. Older structures that utilize the downstream valve design should be monitored closely and owners should plan to relocate the valve upstream or install a new drain structure. Inspectors should closely examine the drain outlet for signs of possible problems.

All reservoirs should have provisions or a plan for water level drawdown during emergencies. Permanent drawdown devices incorporated in the embankment at the time of construction are preferable. Dams that have no drawdown facilities may be retrofitted with siphons for reservoir drawdown. As a last resort, or as a supplement to existing drawdown equipment, standby pumps may be kept near the dam for drawdown. If a pump is used, electrical or fuel supplies must be maintained around the clock.

Figure 3-4 Stem for drawdown control valve located in riser box.

3.3 MECHANICAL EQUIPMENT

Mechanical equipment typically includes spillway gates, sluice gates or valves for reservoir drains or water supply pipes, stoplogs, sump pumps, flashboards, relief wells, emergency power sources, siphons, and other devices. All mechanical and associated electrical equipment should be operated at least once a year, and more often if the equipment systems are complex. The annual test should be conducted through the full operating range under actual operating conditions to determine that the equipment performs satisfactorily. Operating instructions should be checked for clarity and maintained in a secure, but readily accessible location. Each operating device should be permanently marked for easy identification. All operating equipment should be accessible, and equipment controls should be checked for proper security to prevent vandalism.

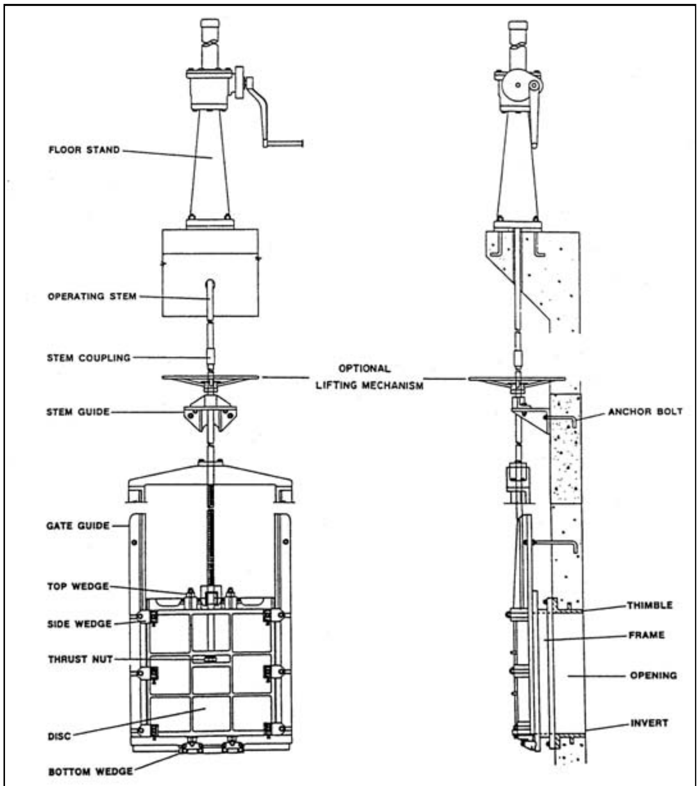

Figure 3-5 Schematic of sluice gate valve.

Many dams have no mechanical or electrical equipment, while some have only mechanical reservoir drain equipment. Earth embankment dams in Indiana typically have no mechanical or electrical equipment, or have an outlet control valve only.

Figure 3-6 Large gates with complex mechanical and electrical equipment.

For dams with mechanical and electrical equipment, all equipment should be checked for proper lubrication, smooth operation, vibration, unusual noises, and overheating. The adequacy and reliability of the power supply should also be checked during operation of the equipment. Auxiliary power sources and remote control systems should be tested for adequate and reliable operation at least monthly. All equipment should be examined for any damaged, deteriorated, corroded, cavitated, loose, worn, or broken parts. Gate stems and couplings should be examined for corrosion, broken or worn parts, and damage to protective coatings. Fluidways, leaves, metal seats, guides, and seals of gates and valves should be examined for damage due to cavitation, wear, misalignment, corrosion, and leakage. Sump pumps should be examined and operated to verify reliability and satisfactory performance. Air vents for pipes, gates and valves should be checked to confirm that they are open and protected. Wire rope or chain connections at gates should be examined for proper lubrication, and worn or broken parts. Rubber or neoprene gate seals should be examined for deterioration, cracking, wear, and leakage. Hydraulic hoists and controls should be operated and checked for oil leaks and wear. Hoist piston and indicator stems should be examined for contamination and for rough areas that could damage packings. All fasteners (bolts and nuts) should be checked to make sure that they are tight; if there is any vibration in the system, chances are that the fasteners will become loose.

Figure 3-7 Stoplogs in spillway.

Many dams have structures above and below ground that require some type of access. Water supply outlet works, reservoir drains, gated spillways, drop inlet spillways, and toe drain manhole interceptors are typical structures that will require bridges, ladders, or walkways. Care should be taken to properly design, install, and maintain these means of access for the safety of persons using them. State and local codes on safety should be followed. Requirements for walkways may include toe plates and handrails. Fixed ladders should have proper rung spacing and safety climbing devices, if necessary. Access ladders, walkways, and handrails should be examined for deteriorated or broken parts or other unsafe conditions. All equipment should be routinely checked and operated as applicable to ensure that it is in good working condition.

Stoplogs, bulkhead gates, and lifting frames or beams should be examined to determine their availability and condition. The availability and locations of equipment for moving, lifting, and placing stoplogs, bulkheads, and trash racks should also be verified. Stoplogs and bulkhead gates may require periodic installation/removal to verify that they can be installed in an emergency.

Flashboards are usually wood boards installed in an upright position along the crest of the spillway to raise the normal pool level. Flashboards should not be installed or allowed unless professional investigation indicates there is sufficient freeboard remaining to safely pass the design flood. Some flash board installations are designed to fail when subjected to a certain depth of flowing water, thereby recovering the original spillway capacity. However, flashboards designed to fail may not be reliable and are not recommended. The support structure for the flashboards should be examined for damage due to wear, misalignment, corrosion, and leakage, and repaired as necessary. The flashboards should be removed periodically (at least once a year) as a check for freedom of movement.

3.4 WINTERIZING TECHNIQUES

Ice can pose problems at spillways and around other structures in reservoirs during the winter months. Ice formation can be prevented by heaters, aeration equipment, or forced movement of water. Ice in conduit outlets or stilling basins can impair their proper functioning, or reduce their discharge capacity. The owner should be aware of these potential problems and take appropriate action during extended periods of severe cold weather if ice will be a problem. Ice damage from impact can also occur during the spring thaw when large chunks of ice begin to break free and strike concrete or metal structures.

Other winterizing activities may include:

(1) Seeding bare areas so that vegetation is established before onset of winter.
(2) Removing flashboards for storage.
(3) Opening valves slightly to provide a small flow to prevent freezing.

The pool level of a reservoir may be lowered for the winter months to facilitate repair of boat docks and other structures, to retard growth of aquatic vegetation, to provide additional spring flood storage, or to prevent ice damage.

3.5 SEDIMENTATION AND DREDGING

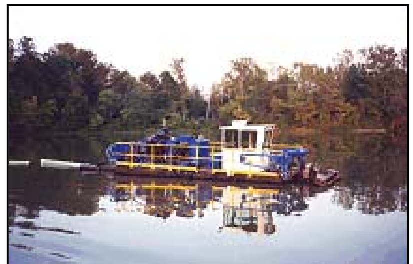

Figure 3-8 Typical dredging operation to remove sediment from a reservoir.

Erosion and sedimentation are natural processes in which soil particles are detached from the earth by raindrops or flowing water and carried by stream flow. Stream velocity, among other factors, determines the capacity of streams to transport sediments. When streams enter lakes, their velocities suddenly drop and the sediment load is deposited on the lake bottom.

Sedimentation occurs in every reservoir, regardless of whether the lake is natural or created by a dam. Sedimentation rates vary widely and depend on many watershed factors. Among these are soil type, land cover, land slope, land use, stream slope, size of watershed, total annual precipitation, number and intensity of severe storm events, material in the streambed, and volume of the reservoir with respect to size of the drainage area. Typically, most of the sediment enters lakes and reservoirs during a few large flood events that occur each year. Sediment deposits first become apparent when deltas build up at the mouths of streams entering the lake. Aquatic vegetation, such as cattails and lily pads, soon develop in the shallow water over these deltas. As sediment deposition continues, the delta will rise above the water surface. Sedimentation can reduce the flood storage capacity of the reservoir, however, sediment removal by dredging may be prohibitively expensive. Therefore, the best practice is to control the sediment within the watershed to keep it out of the reservoir. The best practices to control sedimentation in the watershed area can be found in the “Indiana Drainage Handbook” and the “Indiana Handbook for Drainage Control in Developing Areas.”

For ponds with smaller drainage areas, vegetated strips around the pond will act as filters and trap much of the sediment. These are especially effective for ponds where much of the runoff enters as sheet flow rather than flow from small streams.

3.6 SITE ACCESS

Figure 3-9 Public road on dam crest.

The safe operation of a dam depends on reliable and safe means of access. Usually this involves maintaining a road to the dam. The road should have an all--weather surface and be suitable for the passage of automobiles and any required equipment for servicing the dam. Cut-and-fill slopes uphill and downhill from the road should be stable under all conditions. The road surface should be located above the projected high-water elevations of any adjacent streams and the reservoir pool so access can be maintained at times of flooding.

3.7 VANDALISM

Vandalism is a common problem for all dam owners. Particularly susceptible to damage are the vegetated surfaces of the embankment, mechanical equipment, manhole covers, and rock riprap. Every precaution should be taken to limit access to the dam by unauthorized persons and vehicles. “No trespassing signs” are commonly used to restrict access.

Dirt bikes (motorcycles), off-road-vehicles, and four-wheel drive vehicles can severely damage the vegetation on embankments. Worn areas can lead to erosion and more serious problems. Constructed barriers such as fences, gates, and cables strung between poles are effective ways to limit access of these vehicles to the dam. A highway metal guardrail constructed immediately adjacent to the toe of the downstream slope is an excellent means for keeping vehicles off embankments. However, this may interfere with the operation of mowing equipment.

Figure 3-10 "No Trespassing" signs can help deter vandalism and damage to embankments.

Fishing from embankments can also create problems. Fishermen will often build fires which can kill adjacent vegetation. Fishermen also create paths and may tend to kill the vegetation in areas of repeated use.

Mechanical equipment and its associated control mechanisms should be protected. Buildings containing mechanical equipment should be sturdy, have protected windows and heavy-duty doors, and should be secured with dead bolt locks or padlocks. Detachable controls such as handles and wheels should be removed when not in use and stored inside. Other controls should be secured with locks and heavy chains, where possible. Manhole covers are subject to removal and are often thrown into the lake or spillway by vandals.

Rock used as riprap around dams is occasionally thrown into the lake, spillways, stilling basins, pipe spillway risers, and elsewhere. Riprap is sometimes moved by fishermen to form benches. The best way to prevent this abuse is to use rock too large and heavy to move easily or to slush grout the riprap. Otherwise, the rock must be constantly replenished and other damages repaired.

3.8 PUBLIC SAFETY

Owners should be aware of their responsibility for public safety, including the safety of people not authorized to use the facility. "No Trespassing" signs should be posted and fences and warning signs should be erected around dangerous areas.

Figure 3-11 Outfalls from low head dams are dangerous.

Owners of low-head dams should be aware that these dams are potentially dangerous to boaters and canoeists. During high flow conditions the dam may appear as only a "bump" or ripple in the water surface. This tranquil scene is very deceptive and does not indicate the dangerous conditions that may exist. If a canoe safely negotiates the "bump", backflow just downstream from the dam can act to pull the canoe into the dam and overturn it. The hydraulic action of water passing over the dam creates a "roller" that can trap the victims, continuously pulling them beneath the surface and preventing them from swimming downstream or to the banks. Extremely large riprap (stones weighing 2 to 4 tons each) placed immediately downstream from low-head dams has been effective in breaking up the "roller." A hydraulic engineer should be contacted to properly design any similar corrective measures. Warning buoys, signs, or cable with warning signs stretched across the stream can be effective in discouraging canoeists, but these are often ignored and are difficult to maintain.

3.9 DESIGN MODIFICATIONS

Figure 3-12 This building, constructed in the emergency spillway, reduces discharge capacity.

Alteration of a dam or spillway without adequate engineering design and supervision could result in the spillway or dam being Inadequate in capacity or function. This could lead to a costly repair or complete failure of the structure. In addition, approval by the IDNR of any proposed changes may be required by current state law.

One of the more common errors made by dam owners is raising the normal pool elevation by permanently elevating the crest of the principal spillway. This action not only results in a decrease in storage available during a flood event but also reduces the capacity of the spillway by reducing the hydraulic head (total depth available to "push" water through the spillway). Raising the normal pool will usually cause the emergency spillway to flow more frequently than its design allows, thus increasing its maintenance cost.

Emergency spillways are typically designed to engage only for floods equaling or exceeding the 100-year event. Because the spillway flows so infrequently, owners are tempted to find other uses for it. Temporary uses such as parking or boat launching are acceptable. Permanent alteration of the spillway shape or construction of a building or other structure in the spillway could seriously affect the spillway's ability to function properly and should not be undertaken.

3.10 INSTRUMENTATION AND MONITORING

3.10.1 Overview

Instrumentation refers to the method and equipment used to make physical measurements of dams. The equipment may consist of sophisticated instruments such as permanently installed strain gages for measuring foundation or embankment movements, or may be as simple as a bucket and stopwatch for quick estimates of seepage flows. Monitoring refers to gathering and assimilating data from the instrumentation and evaluating the results. Instrumentation is not a substitute for inspection; it is a supplement to the visual observations made during an inspection. Visual observations combined with instrumentation data provide the basis for assessing embankment and foundation performance and safety during operation of the reservoir. The amount and type of instrumentation used at a dam depends on the type of dam and the conditions encountered. Most dams in Indiana do not have any instrumentation inplace, however, as described below, it is recommended that all dams have a minimum set of measurement capability.

Instrumentation of a dam can provide data to determine if the completed structure is functioning as intended and to provide a continuing surveillance of the structure to warn of any developments, or changes which endanger its safety.

A dam or its appurtenant works will normally experience changes throughout their life. The changes which occur and the factors causing the changes may be identified through the use of instrumentation. Furthermore, instrumentation can make it possible to distinguish between normal and abnormal changes. Knowledge of the changes which occur can enable the dam owner to make intelligent decisions regarding maintenance and repairs. The changes which occur generally include: (1) vertical displacement (settlement); (2) horizontal displacement (change in alignment); (3) internal wetting or saturation of the embankment, and (4) various forms of deterioration (cracking, erosion, weathering, etc.).

Knowing that changes occur is helpful, but more important is understanding the cause. The first changes the dam experiences usually occur during construction. As the height of the dam is increased, the material in the lower portion of the dam is compressed due to the weight of the material on top. The foundation may also compress (settle) due to the weight of the embankment or dam. The changes which occur during construction may not be limited to settlement. For example, instrumentation of earth dams under construction has shown that horizontal displacement (spreading) occurs as well. The first filling of the reservoir will create a new imbalance of forces which may cause more horizontal displacement and additional settlement as the wetting of the embankment progresses. Other factors which cause continual changes are variations in: (1) the depth of stored water; (2) the length of time maximum storage depth is present; (3) seismic activity; (4) seepage of water though or under the dam; (5) adverse weather conditions; and (6) the rate that the reservoir may be drawn down.

A dam instrumentation program must be properly designed and consistent with other project components, must be based on prevailing geotechnical conditions at the dam, and must include consideration of the hydrologic and hydraulic factors present both before and after the project is in operation. The timetable for taking measurements must be established in advance and adhered to, and the methods of data analysis must be appropriate for the type of instruments and conditions being monitored. An instrumentation program should involve instruments and evaluation methods that are as simple and straightforward as the project will allow. The equipment and methods available to monitor conditions that can lead to dam failure include a wide spectrum of instruments and procedures ranging from very simple to very complex. Instruments designed for monitoring potential deficiencies at existing dams must take into account the threat to life and property that the dam presents. Thus, the extent and nature of the instrumentation depends not only on the complexity of the dam and the size of the reservoir, but also on the potential for loss of life and property downstream of the dam. The knowledge and experience of the personnel involved in the design, installation, monitoring, and evaluation of an instrumentation system is of prime importance to the success of the program.

Careful monitoring can prevent costly problems, however sloppy measuring techniques or practices and poorly maintained instrumentation can hide a problem or create a false alarm. Therefore, the owner must have a consistent and systematic approach to monitoring of the dam. Also, by having concise records of the measurements, the owner can quickly determine if a problem is developing. The owner should fully understand the purpose of each instrument in order to understand the use of recorded measurements.

Collecting the data from instrumentation is the first step in a monitoring program. After the data is gathered, it should be reviewed and analyzed by a qualified dam safety professional knowledgeable in dam/foundation responses.

3.10.2 Objectives of Instrumentation and Monitoring

There are four principal objectives for instrumentation and monitoring of dams:

1. Warning of a Problem - Often, instruments can detect unusual changes, such as fluctuations in water pressure, and internal embankment movements that are not visible. In other cases, gradual progressive changes in seepage flow, which would go unnoticed visually, can be monitored regularly. Monitoring can warn of the development of a serious seepage problem. Instrumentation data is often used to predict future behavior of the dam based on current conditions.

2. Analyzing and Defining a Problem - Instrumentation data is frequently used to provide engineering information necessary for analyzing and defining the extent of a problem. For example, downstream movement of a dam because of high reservoir water pressure may be analyzed to determine if the movement is uniformly distributed along the dam, whether the movement is in the dam, the foundation, or both, and whether the movement is continuing at a constant, increasing, or decreasing rate. Such information can then be used to design corrective measures. Cracks can be measured and monitored to determine if they are remaining constant or getting worse. Seepage rates can be measured and monitored with time and with fluctuations in reservoir level. Instrumentation can be very valuable in the determination of the specific cause or causes of problems and failures.

3. Verification of Satisfactory Performance - Instruments may be installed to verify that the dam is performing as expected, to verify the design parameters and assumptions, or to verify construction techniques. Instruments installed at a dam may infrequently (or even never) show any anomaly or problem. However, even this information is valuable because it shows that the dam is performing as designed and provides peace of mind to an owner. In some cases a problem may appear to be occurring or imminent, but instrument readings might show that the deficiency (e.g., increased seepage) is normal and was foreseen in the dam's design (i.e., a result of higher than normal reservoir level).

Table 3-1
Dam Instrumentation Equipment Categorized by Function

1. Deformation
- Hand measuring tools
- Surveying methods
- Probe Extensometers
- Fixed embankment extensometers
- Subsurface settlement points
- Fixed borehole extensometers
- Inclinometers
- Tiltmeter
- Liquid level gages

2. Groundwater pressure
- Open standpipe piezometer
- Twin-tube hydraulic piezometer
- Pneumatic piezometer
- Vibrating wire piezometer
- Electrical wire piezometer
- Pressure cells

3. Water level
- Observation well
- Piezometers
- Water level sensor

4. Seepage flow
- Weirs
- Parshall flumes
- Catch containers and timer
- Velocity meter

5. Water quality
- Laboratory analysis
- Sample jars and visual inspection
- Turbidimeter
- Turbidity sensor

6. Temperature
- Thermistor
- Thermocouple
- Resistance temperature devices
- Density thermometer

7. Cracks and joints
- Hand measuring tools
- Surveying methods
- Joint meter
- Portable crack measuring microscope
- Dial gage
- Mechanical scratch gage
- Crack comparator

8. Seismic activity
- Accelerometer
- Peak acceleration recorders

9. Weather and precipitation
- Precipitation gage
- Wind gage

10. Stress and strain
- Electrical Resistance strain gage
- Vibrating wire
- Hydraulic load cell
- Embeddable strain gage
- Stress gage and meter
- Strain gage and meter

Instrumentation may also be installed to verify that the dam was constructed properly; poor construction practices may result in adverse behavior that can be detected with instrumentation.

4. Evaluating Remedial Action Performance - Many dams, particularly older dams, are modified to allow for increased capacity or to correct a deficiency. Instrument readings taken before and after the change may allow analysis and evaluation of the performance of the modification. The data can be used to determine the effectiveness of the modifications or improvements and the effect of the change(s) on existing conditions.

Instrumentation may also be valuable for providing data for potential litigation relative to construction claims, damage claims from adjacent property owners arising from adverse events, or claims relative to changed water conditions downstream or adjacent to a dam. In some cases, data from instrumentation may be used to develop design criteria and construction techniques for new dams. These reasons for instrumentation may be important when applicable, but they are not considered to be principal objectives.

The types of instrumentation available can be categorized by the conditions that are typically assessed at dams (see Table 3-1). The ten most commonly monitored conditions include the following:

(1) deformation or movements
(2) groundwater pressure
(3) water level
(4) seepage flow
(5) water quality
(6) temperature
(7) cracks and joints
(8) seismic activity
(9) weather and precipitation
(10) stress and strain

Conditions not on the list, such as concrete deterioration, soil erosion, and inadequate vegetation can be monitored with simple instruments, including hand measuring tools and a camera.

3.10.3 Types of Instrumentation

Most of the instrumentation that is used to monitor dam performance is complicated and requires qualified personnel to install and use the equipment. This is especially true for the various instruments available for monitoring concrete structures. Many instruments can be automated and connected to continuous data loggers to simplify data collection. This manual does not provide detailed information for all of the instrumentation that is available, but rather, it focuses on some of the more common, simpler equipment that a typical dam owner is likely to use. Table 3-1 summarizes the types of instruments that are available, categorized by the ten most commonly monitored conditions at dams.

Due to the expense, the use of sophisticated and extensive instrumentation to ensure safety is usually limited to large dams where failure would result in loss of life and a great deal of damage. A full-scale instrumentation and monitoring program requires professional design. The type of instruments and monitoring program that may be deployed depends on the type of conditions encountered and the type of structure being investigated. A brief description of some of the more complex equipment is provided herein to give the dam owner a basic understanding of the principles of these instruments.

Monitoring by private dam owners in Indiana is usually limited to visual observation. It is very important that the observations are accurate, made on a routine schedule, and recorded. An inspection checklist should be used for visual inspections. Owners are encouraged to use photographs with identifying dates and labels as a permanent record to be filed with other dam records.

Simple Monitoring Devices

The following devices are relatively inexpensive and can easily be used by most dam owners to monitor dams.

Camera - Photographs which have been dated and labeled provide an excellent record of existing conditions, and if taken periodically from the same location, can be used for comparison. Photographs should be taken during all inspections to supplement written and visual observations. They are valuable in documenting the location and severity of wet areas, erosion, and concrete deterioration.

Yardstick or folding rule - This portable monitoring device is not only inexpensive but has a number of uses. It can be used to measure cracks, scarps, erosion gullies, settlement, trees, wet areas, and slab or wall movement. Records should be kept of all observations for comparative purposes.

Bucket and Watch - Flow rates in gallons per minute for small weirs, seeps, and pipe outlets can be measured by timing how long it takes to fill a bucket (or other container) of known capacity.

Weirs - The V-notch weir is probably the most commonly used device to measure flow rates of seepage. Effective readings must be taken periodically under similar influences, such as reservoir level and local runoff conditions. Many times after installation, the weirs are neglected and a few good readings become useless for lack of comparative data. Consequently, the V-notch weir must be maintained.

Flumes - For larger flows, the Parshall flume is preferred to larger V-notch weirs because the flume will not restrict the flow as much as the weir. Parshall flumes can be purchased through a supplier of scientific equipment.

Piezometers - Piezometers are instruments used to measure the water pressure in the embankment and foundation soil pores and are installed at various levels in a drill hole. Readings are usually taken by measuring the elevation of water in a standpipe. Seepage pressure can be determined from piezometer readings. Water levels can easily be measured with the use of a portable, battery-operated water-level probe and meter. The probe is lowered into the well or piezometer by means of the electrical cable; when the tip of the probe is submersed, the electrical circuit in the probe is closed and the hand-held meter indicates the presence of water. A water level sensor that measures water pressure can also be used in piezometers to measure water level.

Survey monuments - Survey monuments are usually installed along the crest of the dam to check its vertical and horizontal alignments (with known reference points and elevations). Measurements of these monuments must be precise and are obtained using surveying instruments.

Observations Wells - Observation wells can be installed in the embankment or foundation and are used to determine the ground-water level. The same type of probes used in piezometers can be used in observation wells.

Inclinometers - Inclinometers are instruments that are lowered into a vertical casing and are used to measure horizontal deflection. Inclinometers are often used to determine the rate of movement of a slide. They are usually used to measure internal displacements within earth embankments of higher dams.

Piezometers, settlement monuments, observation wells, and inclinometers are often found on large dams and are described briefly herein. The installation and monitoring of these devices usually requires professional assistance.

Electronic Instrumentation

Most electronic instrumentation consists of three components: a transducer, a data acquisition system, and a linkage between these two components. A transducer is a component that converts a physical change (pressure or movement) into a corresponding electrical output signal. Data acquisition systems range from simple portable readout units to complex automatic systems. Most instruments fall into one of five categories based on the method of operation. A brief, technical description of each category of equipment is provided below.

(1) pneumatic devices
(2) vibrating wire devices
(3) electrical resistance strain gage devices
(4) electrical transducers for measuring linear displacement
(5) other electrical systems

Pneumatic devices

Pneumatic devices measure pressures in the soil with the use of a controlled gas supply. They are typically used for pneumatic piezometers, earth pressure cells, and liquid level settlement gages. The pressure within the soil that is in contact with the instrument probe is the pressure of interest. An increasing gas pressure is applied to the inlet tube of the probe; while the gas pressure in the tube is less than that in the soil, it merely builds up in the inlet tube. When the gas pressure in the tube exceeds the pressure in the soil, a diaphragm in the probe deflects, allowing gas to circulate behind the diaphragm into the outlet tube while the gas flow is sensed using a gas flow detector. The gas supply is then shut off at the inlet valve, and any pressure in the tube that is greater than the soil pressure bleeds away, allowing the diaphragm to return to its original position. When this happens, the pressure in the inlet tube equals the pressure in the soil. This pressure is read on a Bourdon tube or electrical pressure gage. Many detailed issues need to be considered when selecting a pneumatic device, including the sensitivity of the reading to diaphragm displacement, gas flow, tubing length and diameter, type of tubing, tubing fittings, gas, and pressure gage.

Vibrating wire devices

Vibrating wire devices are used in pressure sensors for piezometers, earth pressure cells, liquid level settlement gages, and in numerous deformation gages. In a vibrating wire device, a length of steel wire is clamped at its ends and tensioned so that it is free to vibrate at its natural frequency. As with a piano string, the frequency of vibration of the wire varies with the wire tension. Thus, with small relative movements between the two end clamps of the vibrating wire device, the frequency of the vibration of the wire varies. The movements are caused by pressure being exerted against the end clamps, such as water pressure or earth pressure. The wire can therefore be used as a pressure sensor by measuring the frequency of vibration. The wire is plucked magnetically by an electrical coil attached near the wire at its midpoint, and either this same coil or a second coil is used to measure the period or frequency of vibration. The frequency is proportional to the pressure being applied on the end clamps. Detailed issues that need to be considered when selecting a vibrating wire device include the method of clamping the wire, preventing corrosion or seepage, and pre-treating the transducer to prevent significant zero drift. The attached wire is under near maximum tension at zero pressure. This tension applies the greatest demand on the clamping and annealing of wire, a condition that may cause creeping and slippage of the wire at the clamps, which results in a frequency reduction unrelated to strain. This is commonly known as drift of the baseline pressure or zero drift. With vibrating wire transducers undesirable effects involving signal cable resistance, contact resistance, electrical signal seepage to ground, or length of signal cable are negligible. Very long cable lengths are acceptable.

Electrical resistance strain gage devices

Electrical resistance strain gages are very common and are used in many measurement devices, including strain gages, joint meters, and pressure cells. An electrical resistance strain gage is a conductor with the basic property that resistance changes in direct proportion to change in length. The relationship between resistance change and length change is given by the gage factor. Output from the gages is normally measured using a Wheatstone bridge circuit. Electrical resistance strain gages can be packaged as bonded wire, unbonded wire, bonded foil, and weldable gages. The measured resistance change can be strongly influenced by signal cable length, contact, moisture, temperature, and leakage to ground. However, correction for these influences can be made by measuring the resistance of the various system components (cable, contact, etc.) and subtracting the resistance from the total resistance. Various companies now manufacture low-current signal transducers (4- to 20-milliamp range) that are unaffected by resistance problems.

Electrical transducers for measuring linear displacement

A linear variable differential transformer (LVDT) consists of a movable magnetic core passing through one primary and two secondary coils. An AC voltage is applied to the primary coil, thereby inducing an AC voltage in each secondary coil, with a magnitude that depends on the proximity of the magnetic core to each secondary coil. Changes in pressure or movement are measured as the core-to-coil distance changes proportional to the changes.

A direct current differential transformer (DCDT) is similar to a LVDT, except that unwanted cable effects associated with LVDT’s are avoided by using DC voltages, requiring miniaturizing the electrical circuitry and placing additional components within the transducer housing.

A linear potentiometer is a device with a movable slider, usually called a wiper that makes electrical contact along a fixed resistance strip. A regulated DC voltage is applied to the two ends of the resistance strip and the voltage or resistance between the one end of the strip and the wiper is measured as the output signal. The voltage between the end of the strip and the wiper varies as the wiper moves from one end of the strip to the other.

Other electrical systems

Force balance accelerometers are used as tilt sensors in inclinometers. The device consists of a mass suspended in the magnetic field of a position detector. When the mass is subjected to a gravity force along its sensitive axis, it tries to move, and the motion induces a current change in the position detector. This current change is fed back through a servo-amplifier to a restoring coil, which imparts an electromagnetic force to the mass that is equal and opposite of the initiating gravity force. The mass is thus held in balance and does not move. The current through the restoring coil is measured by the voltage across a precision resistor. This voltage is directly proportional to the input force.

The magnet/reed switch system is used in probe extensometers. It is an on/off position detector, arranged to indicate when the reed switch is in a certain position with respect to a ring magnet. The switch contacts are normally open and one of the reeds must be magnetically susceptible. When the switch enters a sufficiently strong magnetic field, the reed contacts snap closed and remain closed as long as they stay in the magnetic field. The closed contacts actuate a buzzer or indicator light in a portable readout unit.

Induction coil transducers are also used in probe extensometers. An electrical coil is powered to create a magnetic field around the coil. When this coil is placed inside a steel wire ring (with no external electrical connection), a voltage is induced in the ring, which in turn alters the current in the coil because its inductance changes. The current in the coil is a maximum when the coil is centered inside the ring; thus, by measuring current in the coil, the transducer can be used as a proximity sensor.

Sonic transducers can be used to monitor water level in open standpipe piezometers and weir stilling basins. The transducer is mounted above the water surface. Sound pulses travel to the water surface and are reflected back to the transducer. The distance to the water surface is determined from the measured pulse time and the known velocity of sound waves, corrected for errors induced by temperature change.

Resistance temperature devices depend on the principle that change in electrical resistance of a wire is proportional to temperature change. The wire is usually mounted on a postage-stamp-sized backing or wound on a small-diameter coil.

3.10.4 Instrumentation Usage

Instrumentation usage depends on the type of dam and the conditions encountered. A determination of the number, type, and location of instruments required at a dam can only be addressed effectively by combining experience, common sense, and intuition. Dams present unique situations and require individual solutions to their instrumentation requirements. The instrumentation system design, therefore, needs to be planned with consideration for the site-specific geotechnical conditions present in the embankment, foundation, abutments, concrete structure, and reservoir rim. Reasons such as unique design or difficult foundation conditions, severe downstream hazard, visually observed problems or concerns, remoteness of location, normally unmanned operation, or other concerns justify providing instrumentation. Personnel installing field instrumentation must understand the fundamental physics and mechanics involved, and how the various available instruments will perform under the conditions to which they will be subjected.

As discussed earlier, a wide variety of devices and procedures are used to monitor dams, and the installation and operating details of most of the available instruments are beyond the scope of this manual. Therefore, this subchapter presents general guidelines for instrumentation and details for some of the simpler devices that most dam owners can readily deploy. Details of the installation, operation, and maintenance of each device are described in the following publications:

(1) *Embankment Dam Instrumentation Manual*, U.S. Bureau of Reclamation, Government Printing Office, February 1987.
(2) *Guidelines for Instrumentation and Measurements for Monitoring Dam Performance*, American Society of Civil Engineers, September 2000.
(3) *Instrumentation of Embankment Dams and Levees*, EM 1110-2-1908, U.S. Army Corps of Engineers, June 1995.
(4) *Instrumentation for Concrete Structures*, EM 1110-2-4300, U.S. Army Corps of Engineers, November 1987.

Planning an instrumentation and monitoring system requires the consideration of many factors, and a team effort of the designers (or those responsible for evaluating existing projects) and personnel having expertise in the application of instrumentation. Developing an instrumentation system should begin with a definition of an objective and proceed through a comprehensive series of logical steps that include all aspects of the proposed system. Recommended steps for developing an instrumentation system are presented on Table 3-2.

Table 3-2
Steps for Developing an Instrumentation System

- Prediction of mechanisms that control dam behavior
- Definition of purpose of instrumentation
- Definition of geotechnical issues and concerns
- Selection of parameters to monitor
- Prediction of magnitude or range of changes being monitored
- Selection of instrument locations
- Selection of type and make of instruments
- Determination of need for automation
- Planning for recording of factors which influence measurements
- Establishment of procedures for ensuring data validity
- Determination of capital and operating costs
- Preparation of installation plan and schedule
- Planning long-term protection of instruments
- Planning regular calibration and maintenance
- Planning data collection and management
- Coordination of resources and assignment of responsibility
- Determination of life cycle costs

High hazard dams need to be closely monitored on a regular basis because of the potential safety risk they pose to the public. The minimum level of monitoring at every high hazard dam should include the following measures, as applicable:

- Measurement of reservoir water surface elevation (reservoir gage).
- Measurement of drainage and seepage flow rates.
- A survey control network with fixed monuments adjacent to the dam and on the embankment crest.
- A written plan that can allow the owner to monitor deformations and possible movement of dam structures at a moments notice.
- Detailed specifications and installation plans for each instrument that may be used.
- An operation and maintenance manual for each instrument that is used.

Instrumentation Usage by Function

For ease of reference, the most common types of equipment used are categorized based on the conditions most commonly encountered at dams. If the dam owner has a specific monitoring need, he/she should first determine what condition or conditions must be monitored; then, the type of instrument(s) that can be used to best suit the need should be determined. Monitoring equipment can be categorized by the following conditions:

- deformation or movements (horizontal, vertical, rotational, and lateral)
- groundwater pressure (pore pressure and uplift pressures)
- water level
- seepage flow
- water quality
- temperature
- cracks and joints
- seismic activity
- weather and precipitation
- stress and strain

Monitoring equipment that can be used for each of these conditions is described below. As discussed in Part 3 of the Indiana Dam Safety Inspection Manual, visual observations by the dam owner or the owner's representative may be the most important and effective means of monitoring the performance of a dam. The visual inspections should be made whenever the inspector visits the dam site and should consist of a minimum of walking along the dam alignment and looking for any signs of distress or unusual conditions at the dam.

<u>**Deformation or Movements**</u>

Deformation or movements occur in every dam. They are caused by stresses induced by reservoir water pressure, unstable slopes (low shearing strength), low foundation shearing strength, settlement (compressibility of foundation and dam materials), thrust due to arching action, expansion resulting from temperature change, and heave resulting from hydrostatic uplift pressures. Movements can be categorized by direction, including horizontal, vertical, rotational, and lateral.

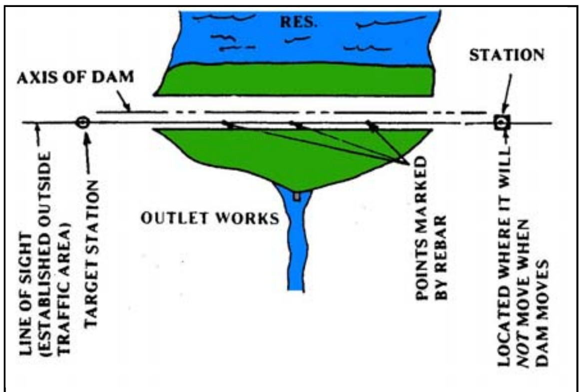

Figure 3-13a Schematic of survey control plan for monitoring alignment and settlement.

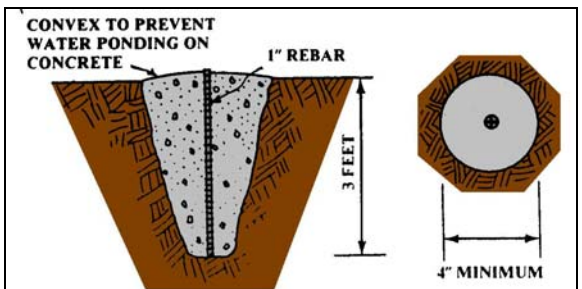

Figure 3-13b Schematic of section through a permanent survey monument. (Note that the sides of the monument should be vertical if frost heave is a concern.)

Monitoring movements (also called displacements) can be helpful in understanding the normal behavior of a dam as well as being useful in determining if a potentially hazardous condition is developing. The displacements are more commonly measured on the surface of the embankment or concrete structure. Measuring displacements of points on the surface is usually accomplished by conventional surveying methods such as leveling or alignment. The movements are not limited to just the embankment or dam, but can sometimes be traced to a point below the dam in the foundation. Internal displacement monitoring schemes can be complex and expensive. Therefore, the measurement of displacements is usually monitored on the surface, unless a problem develops.

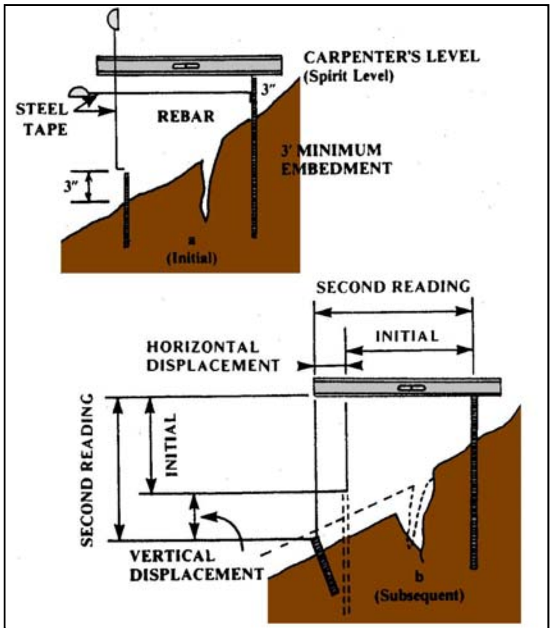

Figure 3-14 Simple system for monitoring cracks and slope displacement.

Horizontal Movement

Horizontal, or translational, movement commonly happens in an upstream-downstream direction in both embankment and concrete dams. It involves the movement of an entire dam mass relative to its abutments or foundation. Cracks are usually present during horizontal movement. Vertical, rotational, and lateral movements often occur in conjunction with horizontal movement.

In an embankment dam, instruments commonly used for monitoring horizontal movement include:

- extensometers
- multi-point extensometers
- inclinometers
- shear strips
- structural measuring points
- embankment measuring points

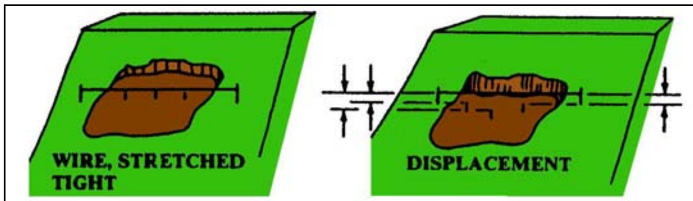

Figure 3-15 Simple technique for monitoring slides.

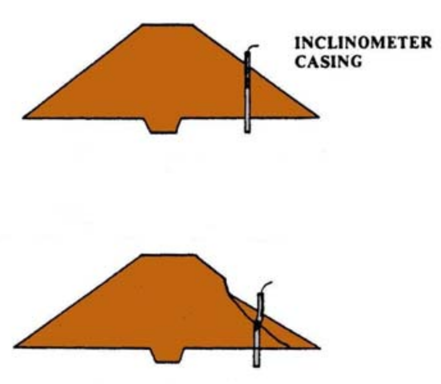

Figure 3-16 Inclinometer probes are used to detect horizontal displacement of the casing.

Installation of simple measuring points is an easy way to monitor horizontal movements. A simple system for monitoring displacements on the surface consists of a few permanent points across the crest of the dam (see Figures 3-13 a and b). The points are usually marked with a 3-foot length of 1-inch diameter rebar set in concrete. The alignment system measures the change in the point's position relative to the line of sight. Subsequent measurements are compared with the initial. The amount of horizontal displacement from the line-of-sight and the change in elevation (vertical movement) from the initial is reported. The rate of settlement and horizontal displacement with time or reservoir gage height can be observed. The single line-of-sight system can be expanded to include two or even three lines-of-sight to monitor points across the upstream and downstream face. More often the alignment monitoring system is used to establish behavior patterns of the dam especially during filling of the reservoir or during the construction of modifications to the dam.

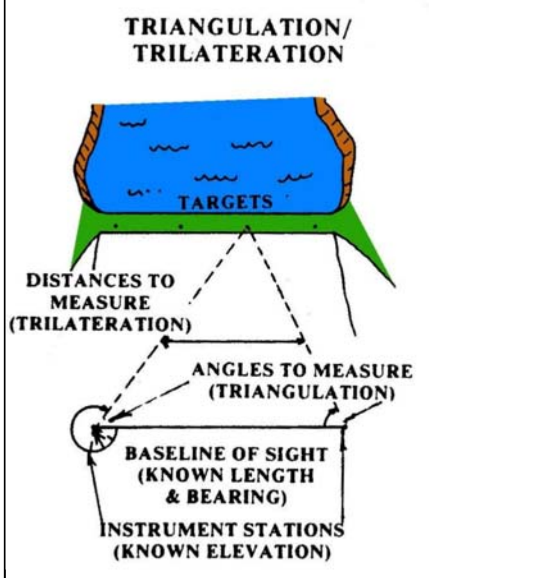

Figure 3-17a Schematic of triangulation/trilateration plan.

For dams with a long crest length, the line-of-sight can be excessively long. In this case, the line of sight is frequently moved downstream of the dam and becomes a baseline. Displacements are monitored by turning angles from fixed points, or stations, on the baseline to points on the dam. The system forms triangles and is known as triangulation. Instead of measuring angles, the horizontal distances between the end points of the baseline and points on the dam may be monitored using electronic distance measuring (EDM). The distance measuring scheme is known as trilateration. Triangulation and trilateration are strictly for horizontal control.

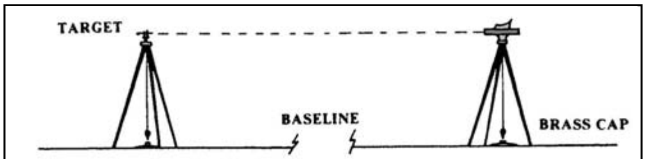

Figure 3-17b Establishing a baseline for triangulation/trilateration.

The survey instrument is positioned over the station. A target is placed on the other instrument station and at the point to monitor on the dam. Once the sight on the baseline is established the angle between the baseline and the line to the target is measured. After measuring angles to all targets, the instrument is moved to the other station and the other angles from the baseline to the targets are measured. The most common source of error typically is not having the instrument exactly plumb.

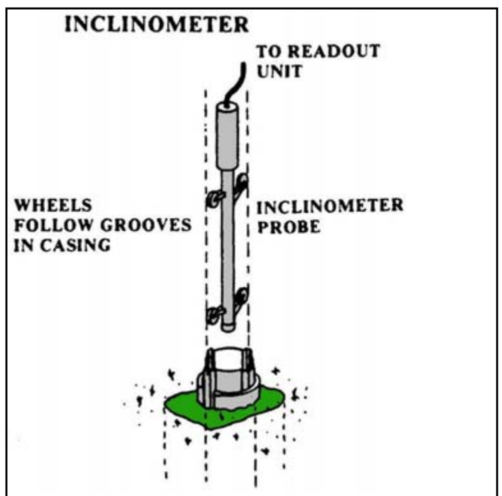

Figure 3-18a Inclinometer surface installation detail.

The owner is frequently faced with special situations where the temporary and immediate monitoring of potentially dangerous conditions is needed. Sometimes this calls for a little imagination on the part of the owner and the use of common materials.

A simple method of monitoring cracks on embankments is to drive rebar or stakes on both sides of the crack(s) to monitor any additional separation and vertical displacement on one side of the crack relative to the other side. Also, the

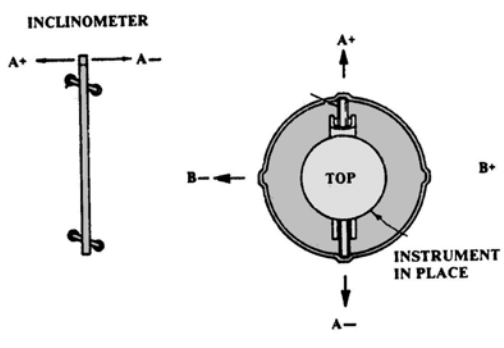

Figure 3-18b Inclinometer casing detail.

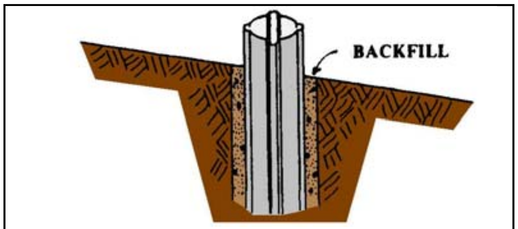

Figure 3-18c Inclinometer casing installation detail.

end of the crack should be staked to determine if the crack is lengthening. This scheme can be used to monitor both longitudinal and transverse cracking (see Figure 3-14).

Another special situation which would require immediate attention is a slide. The method of monitoring is simple yet reliable and utilizes the same principle as the alignment method. A strong wire is stretched across the slide and tied to pins outside the slide area. At intervals along the wire, pins are driven into the slide mass as shown on the left. If additional movement occurs, the amount is directly determined by measuring the distance between the pins and the wire (see Figure 3-15).

Inclinometers are used to monitor internal displacements of the embankment or movements in the foundation. The purpose and advantage of making measurements of internal movements are that the movements will undoubtedly be detected before the effects appear on the surface. The embankment and foundation deforms and causes the surface to move. Therefore, surface monitoring of displacements does not always tell the entire story of "what is happening." The inclinometer is designed to measure horizontal movements of the embankment and/or the foundation at any depth below the surface. The system consists of a special casing with grooves on the inside at the quarter points.

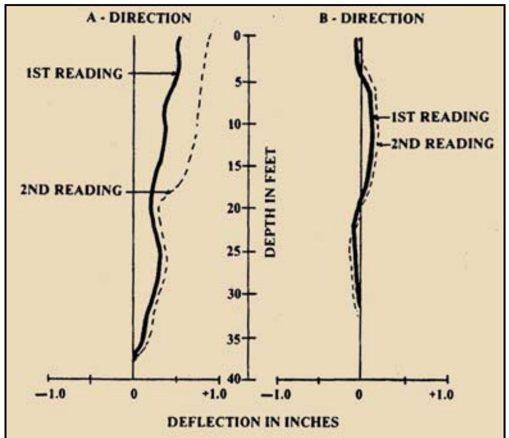

Figure 3-19 Plot of inclinometer readings.

The inclinometer is installed in the embankment portion of a dam. The inclinometer probe will detect small horizontal displacements of the casing. Many times the displacements are small but can be a sign of internal movement of the dam. Being able to detect small internal movements can warn against a large movement before it is observed on the surface as a crack or slide. The inclinometer readings should be plotted on a table or a graph, such as the one shown on Figure 3-19 to monitor the changes with time. A qualified dam safety professional should be consulted to determine the location and supervise the installation of inclinometers.

It should be emphasized that the more elaborate the scheme for monitoring surface movements, the more important it is to consult a qualified dam safety professional or land surveyor.

For a concrete dam, instruments for monitoring horizontal movements may include:

- crack measuring devices
- extensometers
- multi-point extensometers
- inclinometers
- structural measuring points
- tape gauges
- strain meters
- plumb lines
- foundation deformation gauges

The owner should also concentrate on monitoring changes in the concrete structures associated with the dam, such as the spillway and outlet works. The owner should monitor vertical and lateral displacements in addition to horizontal movement. Structural cracking and tilting of walls in spillways or the drop structure for the outlet are common forms of movement. Simple methods for monitoring movements on concrete structures are illustrated on Figures 3-20 and 3-21.

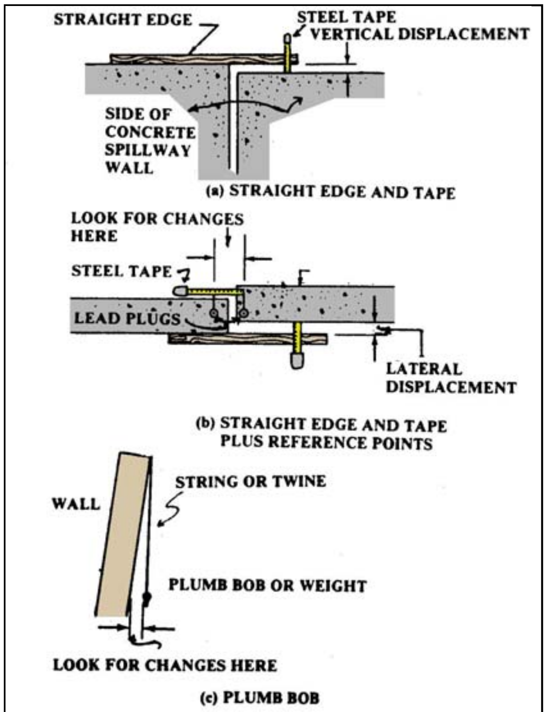

Figure 3-20 Simple method for monitoring concrete displacement.

Vertical Movement

Vertical movement is commonly a result of consolidation of embankment or foundation materials resulting in settlement of the dam. Another cause is heave (particularly at the toe of a dam) caused by hydrostatic uplift pressures. In an embankment dam, vertical movements may be monitored by:

- settlement plates/sensors
- extensometers
- piezometers
- vertical internal movement devices
- embankment measuring points
- structural measuring points
- inclinometer casing measurements

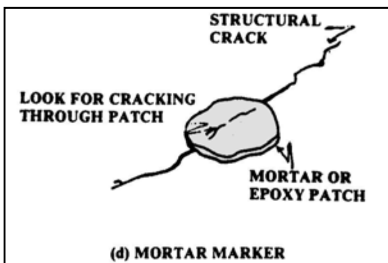

Figure 3-21 A concrete patch can be used to monitor movement.

In a concrete dam, vertical movement monitoring devices may include:

- settlement sensors
- extensometers
- piezometers
- structural measuring points
- foundation deformation gauges

Rotational Movement

Rotational movement is commonly a result of high reservoir water pressure in combination with low shearing strength in an embankment or foundation and may occur in either component of a dam. This kind of movement may be measured in either embankment or concrete dams by instruments such as:

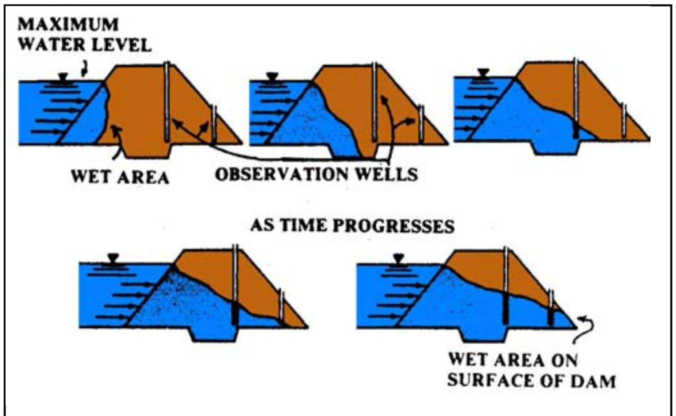

Figure 3-22 Observation wells can be used to monitor water levels, or phreatic surface, in the embankment.

- extensometers
- inclinometers
- tiltmeters
- surface measurement points
- crack measurement devices
- piezometers
- foundation deformation gauges
- plumb lines (concrete only)

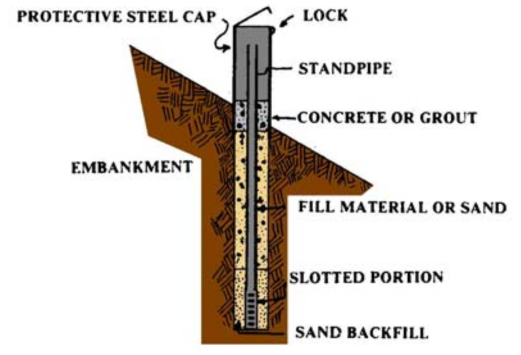

Figure 3-23 Schematic of observation well installation.

Lateral Movement

Lateral movement (parallel with the crest of a dam) is common in concrete arch and gravity dams. The structure of an arch dam causes reservoir water pressure to be translated into a horizontal thrust against each abutment. Gravity dams also exhibit some lateral movement because of expansion and contraction due to temperature changes. These movements may be detected by:

- structural points
- tiltmeters
- extensometers
- crack measurement devices
- plumb lines
- strain meters
- stress meters
- inclinometers
- joint meters
- thermometers
- load cells

Water Level

For most dams, it is important to monitor the water level in the reservoir and the downstream pool regularly to determine the quantity of water in the reservoir and its

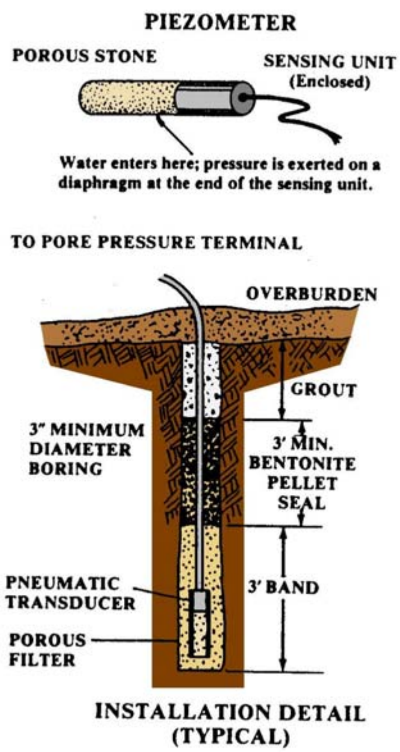

Figure 3-24 Piezometers are used to monitor groundwater pressure.

level relative to the regular outlet works and the emergency spillway. The water level is also used to compute water pressure and pore pressure; the volume of seepage is usually directly related to the reservoir level. It is also important to establish the normal or typical flow through the outlet works for legal purposes. Water levels may be measured by simple elevation gages (either staff gages or numbers painted on permanent, fixed structures in the reservoir), or by complex water level sensing devices.

Flow quantities can be computed from knowledge of the dimensions of the outlet works and the depth of flow in the outlet channel or pipe. Flow meters, flumes, and weirs can also be used if a more accurate determination is needed. A simple, inexpensive technique consists of using a bucket or other container of known volume and a watch to collect and measure the time it takes to fill the container.

Internal water levels must also be monitored to establish the phreatic surface within the embankment. Water in an earth embankment enters the observation well standpipe through the slotted portion and rises to the same level as the water in the soil around the observation well. Each reading of an observation well should be compared to previous readings. A change in the reading should be evaluated as follows:

1. Draw a profile of the water surface on the cross section of the dam along with the reservoir water surface.
2. If the profile appears normal or what can be expected for the current height of the reservoir water surface, continue the normal monitoring program.
3. If the profile appears unusual, it may indicate a potentially dangerous situation. Contact a qualified dam safety professional to discuss the results.
4. Graphs should also be maintained showing the entire history of the observation well measurements. The format of the graphs should make them easy to update after each measurement. This will enable the observer to see the relationship between the current reading and previous readings graphically.

Groundwater Pressure

Water seeps through, under, and around the ends of all dams. The water moves through pores in the soil, rock, or concrete as well as through cracks, joints, etc. The pressure of the water as it moves acts uniformly in all planes and is called pore pressure. The upward force (called uplift pressure) has the effect of reducing the effective weight of the downstream portion of a dam and can materially reduce dam stability. Pore pressure in an embankment dam, a dam foundation, or abutment, reduces that component's shearing strength. In addition, excess water, if not effectively channeled by drains or filters, can result in progressive internal erosion (piping) and failure. Pore pressures can be monitored with the following equipment:

- piezometers (electrical, open standpipe, pneumatic, hydraulic, porous tube, slotted pipe)
- pressure meters & gauges
- load cells

The components of open standpipe piezometers are identical in principle to components of an observation well, with the addition of subsurface seals which isolate the zone of interest. Readings can be made by sounding with a water level indicator, with a pressure transducer placed in the standpipe below the lowest piezometric level, or with a sonic transducer.

Unlike the observation well, which directly shows the height of water in the embankment or foundation, a piezometer indicates the pressure exerted by the height of water above the tip of the piezometer. The piezometer measures the pressure of water entering the porous filter stone in the well. In the case of an earth dam the pressure is primarily due to the infiltration of water into the embankment from the reservoir. The pressure exerted on the piezometer is a function of the height reached by the water in the embankment above the piezometer. The advantage the piezometer has over the observation well is the ability to measure small changes in the water level above it. A piezometer also has a more rapid response to changes of water pressure in the embankment. The piezometer can also sense changes in the water pressure created by factors other than increase in the water level in the embankment. A piezometer can be installed in the foundation under the embankment, or at any other level in the soil. A qualified dam safety professional should be consulted to evaluate the need and supervise the installation of piezometer. There are several types of piezometer available (i.e., open tube, hydraulic, pneumatic, electric, etc.). Selection of piezometers is made based on use, cost, and availability.

Twin-tube hydraulic piezometers utilize a twin-tube system to determine groundwater pressure. The piezometric elevation is determined by adding the pressure gage reading to the elevation of the pressure gages. If both tubes are completely filled with liquid, both pressure gages should indicate the same pressure. However, if gas has entered the system (through the filter, tubing, or fittings) the gas will cause an inaccurate pressure reading on one or both gages. The gas must be removed by flushing. Dual gages therefore indicate the need for flushing and re-calibration.

Pneumatic piezometers utilize the principle of differential gas pressure described earlier. A filter is added to separate the flexible diaphragm from the material in which the piezometer is to be installed. A special type of pneumatic piezometer is available for installation by pushing into foundation material, rather than by drilling and subsurface sealing. The piezometer is pushed below the bottom of a borehole, and the borehole is filled with a soft bentonitic grout. Great care must be taken during installation to avoid damaging the lead connection to the sensor.

Vibrating wire piezometers are based on the use of a pressure sensor. A filter is added, and permanent embedded installation arrangements can be similar to those for an open standpipe piezometer. Special heavy-walled versions are available for installation in compacted fills, the heavy wall ensuring that the instrument responds only to changes in pore water pressure, and not to total stresses acting on the housing. Special versions are also available, similar to the pneumatic piezometer, for monitoring consolidation pore water pressures below embankments where vertical compression of the foundation material is large.

Electrical resistance piezometers are based on the strain gages. The vent tubes have been known to block and invalidate readings.

All piezometers include an intake filter. The filter separates the pore fluid from the structure of the soil in which the piezometer is installed and must be strong enough to avoid damage during installation and to resist the total stresses without undue deformation. Filters can be classified in two general categories: high air entry and low air entry. Filters keep fluids in equilibrium by balancing the pressure differential with surface tension forces at the gas/water interface. The finer the filter, the greater can be the pressure differential. The air entry value or bubbling pressure of the filter is defined as the pressure differential at which blow-through of gas occurs. Thus, a filter with a high air entry value (or high bubbling pressure) is a fine filter that will allow a high pressure differential before blow-through occurs.

Low air entry filters are coarse filters that readily allow passage of both gas and water, and should be used for all piezometer types that are installed in saturated soils and for open standpipe piezometers installed in unsaturated soils. Filters should be saturated when installed. They can readily be saturated with water prior to installation by soaking or by passing water through the pores.

High air entry filters are fine filters that must be used when piezometers (except open standpipe piezometers) are installed in unsaturated soil, such as the compacted core of an embankment dam, with the intent of measuring pore water pressure as opposed to pore gas pressure, in an attempt to keep gas out of the measuring system. Saturation of high air entry filters requires a much more controlled procedure, entailing removal of the filter from the piezometer, placing the dry filter in a container, and applying a vacuum. The filter should then be allowed to flood gradually with warm de-aired water.

When using piezometers, reliability and durability are often of greater importance than sensitivity and high accuracy. Therefore, the designer's intent for the use of the instrument is crucial to the selection of the type of instrument. The fact that the actual head may be in error by as much as 1 ft, as a result of time lag, may not matter in some cases, provided the piezometer is functioning properly. Piezometer installations with transducers may require corrections for barometric pressure if high accuracy is needed.

For measurement of piezometric pressure in saturated soil, an open standpipe piezometer is the first choice and should be used when applicable. Limitations associated with extending the standpipe through embankment fill normally prevent their use within the fill of an embankment dam. When any of these limitations are unacceptable, a choice must be made among the remaining piezometer types.

For short-term applications, defined as applications that require reliable data for a few years (for example during the typical construction period), the choice is generally between pneumatic and vibrating wire piezometers. The choice will depend on the site factors, on the user's own confidence in one or the other type, and on a comparison of cost of the total monitoring program.

For long-term applications twin-tube hydraulic piezometers and Casagrande piezometers have become attractive options because of their basic simplicity and reliability.

For monitoring consolidation pore water pressures below embankments, in cases where vertical compression of the foundation material is large, the push-in pneumatic or vibrating wire piezometers are good choices. Push-in versions of open standpipe piezometers are also available.

When the economics of alternative piezometers are being evaluated, the total cost should be determined, considering costs of instrument procurement, calibration, installation, maintenance, monitoring, and data processing. The cost of the instrument itself is rarely the controlling factor and should never dominate the choice.

If the pores in a soil contain both water and gas, such as in the compacted clay core of an embankment dam or in an organic soil deposit, the pore gas pressure will be greater than the pore water pressure. In fine-grained soils, the pressure difference can be substantial, and special techniques are required to ensure measurement of pore water pressure rather than pore gas pressure. For all piezometer types other than open standpipe piezometers, these techniques include use of high air entry filters, saturated before use, with the filter in contact with the unsaturated soil. Intimate contact will not be achieved if the filter is on the flat end of a cylindrical piezometer; the filter must be on the side or on a conical end. The piezometer should not be installed in a sand pocket.

Piezometer selection criteria for a soil containing both water and gas are similar to those described earlier for saturated soil. For short-term applications, the choice will generally be among open standpipe, pneumatic, and vibrating wire piezometers. For long-term applications the longevity of filter saturation is uncertain because gas may enter the filter by diffusion. The compacted fill in an embankment dam may remain unsaturated for a prolonged period after the reservoir is filled, and in fact the fill may never become permanently saturated by reservoir water. Increase of water pressure causes air to go into solution, and the air is then removed only when there is enough flow through the fill to bring in a supply of less saturated water. The pressure and time required to obtain saturation depend on the soil type, degree of compaction, and degree of initial saturation. Pore gas pressure may therefore remain significantly higher than pore water pressure for a substantial length of time, perhaps permanently. Pneumatic and vibrating wire piezometers therefore cannot be relied upon for monitoring long-term pore water pressures. However, twin-tube hydraulic piezometers allow for flushing of the filter and cavity with de-aired liquid, thereby ensuring that pore water pressure continues to be measured. The choice for long-term reliable measurement of pore water pressure is therefore between open standpipe and twin-tube hydraulic piezometers.

Seepage Flow

The potential for a dam to leak, or seep, will vary according to the design of the embankment, the ability of the cutoff to prevent leakage under the dam, and the tightness of the natural abutments. Seepage should first appear at the toe drain if the dam was constructed with a drain system. If the dam does not have a drain system, seepage may appear on the downstream face.

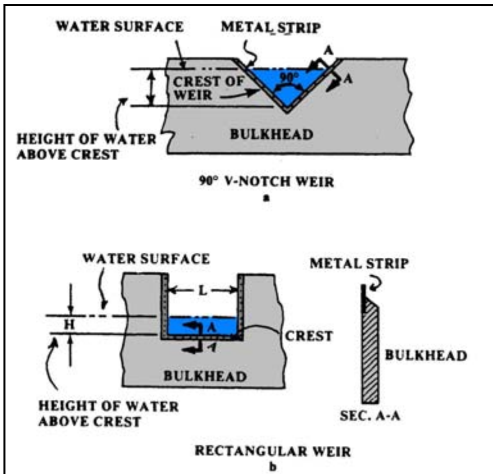

Figure 3-25 Schematic of common weirs.

Seepage should be monitored on a regular basis to determine if it is increasing or decreasing, or remaining constant as the reservoir level fluctuates. A flow rate changing relative to a reservoir water level can be an indication of a clogged drain, piping, or internal cracking of the embankment. Seepage may be measured using the following devices and methods:

- weirs (any shape such as V-notch, rectangular, trapezoidal, etc.)
- flumes (such as a Parshall flume)
- pipe methods
- timed-bucket methods
- flow meters
- observation Wells

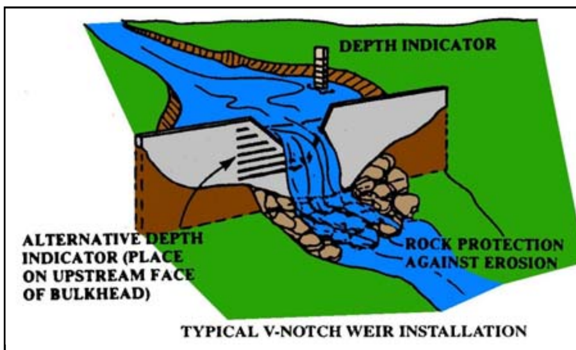

Figure 3-26 Typical V-notch weir installation.

Weirs, flumes, and dikes can be installed to measure seepage, especially seepage exiting from the embankment or foundation at random point sources. When properly calibrated and kept free of silt and vegetation, weirs and flumes can measure seepage accurately. These devices can also be used downstream of general seepage areas where the water flows into a ditch or channel. Weirs and flumes that are silted-in may indicate that the embankment or foundation material is being piped out of the dam, or sediment from surrounding surface runoff erosion is collecting in the structure. If weirs and flumes become silted-in, the situation should be carefully evaluated to determine the cause of the siltation. Dikes can be installed across a channel or ditch with a pipe installed to measure flow also, as shown in Figure 3-28.

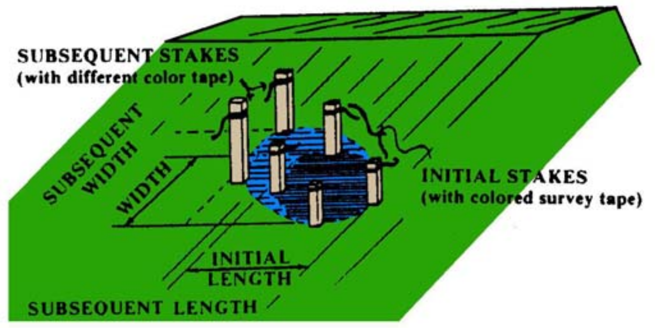

Figure 3-27 Simple technique for staking and monitoring seepage progression.

If the area is damp from seepage, the perimeter of the wet area should be staked out and the length and width of the area should be recorded. Also the degree of wetness, such as boggy, surface moist but firm underfoot, etc., should be described. An example of staking wet areas is shown on Figure 3-27.

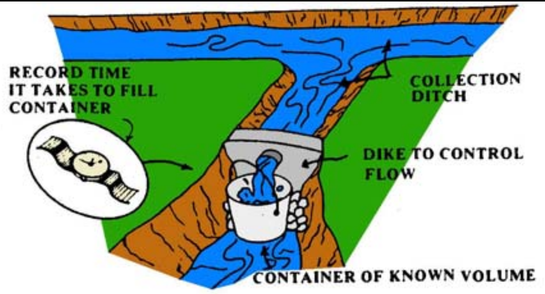

Figure 3-28 Measuring seepage flow with simple tools.

When the leak produces a measurable flow of water, the quantity should be monitored. First, confine the flow through drainage channels away from the embankment. Then measure the quantity flowing by creating a drop in the drainage channel and installing a pipe, a weir, or a flume. The most accurate and direct measurement can be obtained by catching the flow from a pipe in a container of known volume and timing how long it takes to fill the container as shown in Figure 3-28. The flow rate should be recorded in gallons per minute.

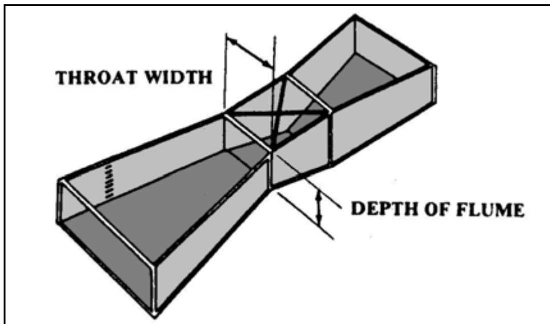

Figure 3-29 Schematic of Parshall flume.

A weir, on the other hand, can save time, but the measurement is not as direct as the bucket and stop watch. The rate of flow at a weir is related to the height of water flowing over the crest of the weir. The most commonly used are the V-notch and rectangular weirs.

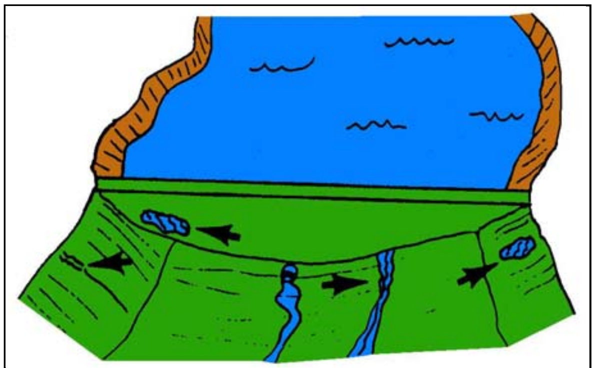

Figure 3-30 Drawing a sketch of seepage areas is a good way to record observed conditions.

For larger flows, the Parshall flume is preferred to larger weirs because the flume will not restrict the flow as much as the weir. Parshall flumes like that shown on Figure 3-29 can be purchased through a manufacturer and is shown here only as a guide to help the owner understand the methods used to measure seepage quantities. Table 3-5 presents approximate

Table 3-3 Discharge of 90-degree V-Notch Weirs			
Head, H in Ft	Approx. Flow In GPM	Head, H in Ft	Approx. Flow In GPM
0.10	4	0.42	129
0.12	6	0.44	145
0.14	8	0.46	162
0.16	12	0.48	180
0.18	16	0.50	200
0.20	21	0.52	220
0.22	26	0.54	241
0.24	32	0.56	264
0.26	39	0.58	288
0.28	47	0.60	314
0.30	56	0.62	340
0.32	66	0.64	368
0.34	77	0.66	397
0.36	88	0.68	428
0.38	101	0.70	460
0.40	115	0.72	493

Table 3-4 Discharge of Standard 1-ft Contracted Rectangular Weir			
Head, H in Ft	Approx. Flow In GPM	Head, H in Ft	Approx. Flow In GPM
0.02	4	0.28	209
0.04	12	0.30	231
0.06	22	0.32	253
0.08	33	0.34	276
0.10	46	0.36	300
0.12	61	0.38	324
0.14	76	0.40	348
0.16	93	0.42	373
0.18	110	0.44	398
0.20	128	0.46	423
0.22	147	0.48	449
0.24	167	0.50	476
0.26	188		

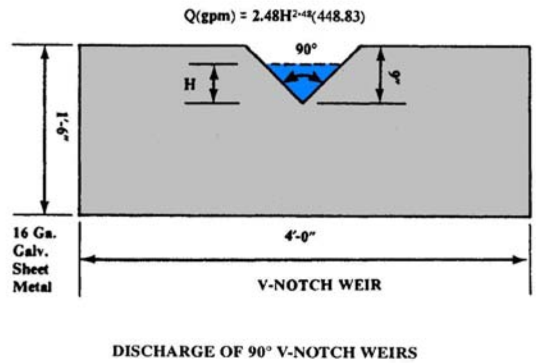

Figure 3-31 Dimensions of 90-degree V-notch weir.

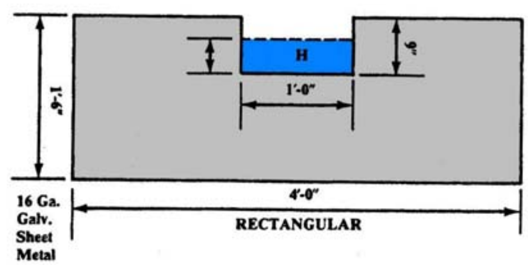

Figure 3-32 Dimensions of rectangular weir.

Table 3-5 Typical dimensions of Parshall flumes.

Rated Capacity		Throat Width	Depth	Weight	Thickness	Intake Width	Overall Length
cfs	gpm	In.	In.	Lbs	gage	In.	ft
0.082	32	1	6	13	16	6.59	2.08
0.469	210	2	10	25	16	8.41	2.54
0.640	287	3	12	55	12	10.19	3.00
1.134	509	3	18	41	16	10.19	3.00

flow quantities for some Parshall flumes of various sizes.

The reservoir gage rod height should be recorded along with seepage quantities. It is also helpful to have a site map or sketch describing the location and extent of the seepage similar to the sketch shown on Figure 3-30. All pertinent features of topography and sources which may be contributing to the seepage should be included on the map or sketch. A photograph of the seepage or wet area is also helpful in describing the situation.

Water Quality

Seepage comes into contact with various minerals in the soil and rock in and around the dam. This can cause two problems: the chemical dissolution of a natural rock such as limestone, or the internal erosion of soil. Dissolution of minerals can often be detected by comparing chemical analyses of reservoir water and seepage water. Such tests are site specific; for example, in a limestone area, one would look for calcium and carbonates; in a gypsum area, calcium and sulfates. Other tests, such as ph can also sometimes provide useful information on chemical dissolution. Internal erosion can be detected by comparing turbidity of reservoir water with that of seepage water. A large increase in turbidity indicates erosion.

Figure 3-33 Turbid water exiting a pipe under an embankment.

An accurate measurement of leakage quantities along with changes in the turbidity and amount of sediment in the water may be an indication of the beginning or progression of piping. Turbidity is a measure of the amount of soil particles suspended in the water. A visual description would be the color, e.g., clear, cloudy, etc. The sediment will usually be larger particles (silt, sand, small gravel) which settle out in a jar sample of the water. An increase in the turbidity or sediment may indicate that the water is carrying soil with it as it travels through the dam, a very dangerous condition. Each time the quantity is measured, an evaluation of the turbidity and sediment should be made to observe any change. The easiest method of comparing observations is to collect a sample of the water in a quart jar marked with the date collected and retain the sample. A different jar should be used until five or six samples have been collected. Then the jars can be reused, starting with the one containing the oldest sample. This way each new sample can be compared with the previous samples to observe any change in the turbidity or amount of sediment in the water. The water can be removed and the amount of sediment in the bottom of the jar can be weighed for a more accurate measurement.

A good way of detecting a change in turbidity is to collect a number of water samples as follows:

(1) Collect a sample of the water in a quart jar. Date the jar and note the level of clarity. Store the jar in a safe location.
(2) Repeat step 1 each time seepage flow is measured until several samples have been collected.
(3) Each time a sample is collected, shake up each jar and visually compare the new sample with the samples collected previously. Look for changes in the cloudiness of the samples. Also note the amount of sediment that accumulates in the bottom of the jars as suspended material settles out.

If seepage is clear, but it is suspected that it contains dissolved material from the foundation (because, for instance, seepage has increased without any signs of turbidity), it may be necessary to perform water quality testing.

The rate and turbidity of seepage flow should be recorded at each inspection. If seepage problems are suspected, then the frequency of inspections should be set by a qualified dam safety professional. If seepage problems do occur, further testing should be conducted by a qualified dam safety professional.

Temperature

The internal temperature of concrete dams is commonly measured both during and after construction. During construction, the heat of hydration of freshly placed concrete can create high stresses which could result in later cracking. After construction is completed and a dam is in operation, it is not uncommon for very significant temperature differentials to exist depending on the season of the year. For example, during the winter, the upstream face of a dam remains relatively warm because of reservoir water temperature, while the downstream face of the dam is reduced to a cold ambient air temperature. The reverse is true in the summer. Temperature measurements are important both to determine: causes of movement due to expansion or contraction and to compute actual movement. Temperature measurements can be made by using any of several different kinds of embedded thermometers or by making simultaneous temperature readings on devices such as stress and strain meters which provide means for indirectly measuring temperature of the mass.

Cracks and Joints

Knowledge of the locations and widths of cracks and joints in concrete dams, in concrete spillways, and other concrete appurtenances of embankment dams is important because of the potential for seepage through those openings. It is even more important to know if the width of such openings is increasing or decreasing. Various crack and joint measuring devices are available, and most allow very accurate measurement. Some use simple tape or dial gauges, while others use complex electronics to gain measurements.

Concrete cracks can be measured with a crack comparator, which is a hand held microscope with a scale on the lens closest to the surface being viewed. The scale includes lines of various thicknesses which can be compared to the crack. A more simple form of comparator consists of a clear plastic card printed with lines of various thicknesses. Crack movement can be measured with a crack measuring device which is attached to the concrete structure at the crack. This device gives direct readings of crack displacement and rotation.

Underwater inspection and measurement of concrete may be performed by divers, or by manned or unmanned underwater vehicles for very deep water conditions. Either way, cracks on the concrete surfaces can be photographed, videotaped, or measured with measuring tools.

As mentioned earlier, cracks are usually associated with movements, and the measurement of the crack widths and lengths is an indication of the amount of movement.

Seismic Activity

Seismic measuring devices record the intensity and duration of large-scale earth movements such as earthquakes. Many federal and state dams use these instruments because they are part of the U.S. Geological Survey's network of seismic recording stations. It may or may not be necessary for a private dam to contain any seismic devices depending upon whether it is in an area of significant seismic risk. Seismic instruments can also be used to monitor any blasting conducted near a dam site.

Weather and Precipitation

Monitoring the weather at a dam site can provide valuable information about both day-to-day performance and developing problems. A rain gauge, thermometer, and wind gauge can be easily purchased, installed, maintained, and monitored at a dam site.

Stress and Strain

Measurements to determine stress and/or strain are common in concrete dams and to a lesser extent, in embankment dams. The monitoring devices previously listed for measuring dam movements, crack and joint size and temperature are also appropriate for measuring stress and strain. Monitoring for stress and strain permits very early detection of movement. Earth pressure cells may be installed at the contact between the structure and soil during construction to measure stress.

Monitoring Frequency

The frequency of instrument readings or making observations at a dam depends on several factors including the following factors:

- relative hazard to life and property that the dam represents
- height or size of the dam

- relative quantity of water impounded by the dam
- relative seismic risk at the site
- age of the dam
- frequency and amount of water level fluctuation in the reservoir

In general, as each of the above factors increases, the frequency of monitoring should increase. For example, very frequent (even daily) readings should be taken during the first filling of a reservoir, and more frequent readings should be taken during high water levels and after significant storms and earthquakes. As a rule of thumb, simple visual observations should be made during each visit to the dam and not less than monthly. Daily or weekly readings should be made during the first filling, immediate readings should be taken following a storm or earthquake, and significant seepage, movement, and stress-strain readings should probably be made at least monthly.